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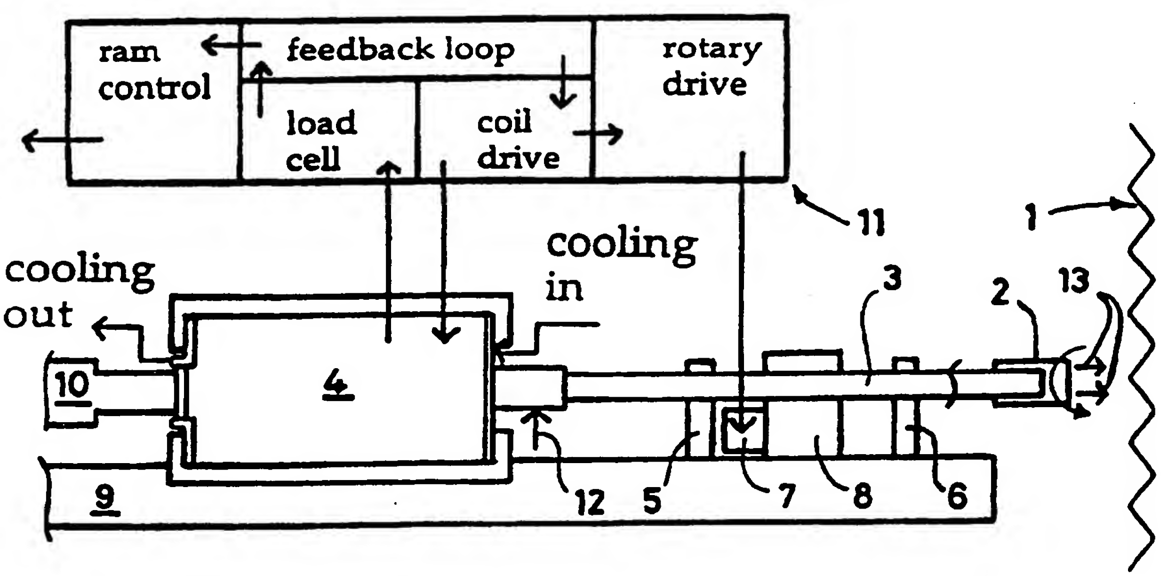

(57) Abstract

This invention relates to a magnetostrictive actuator, in particular for a percussive rock drill. The actuator comprises an applicator (4, 10, 11) with a magnetostrictive unit (4) having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field. The drive means has a plurality of coils supplied in parallel with an electric drive current pulsed at a drive frequency from one or more drive circuits. A biasing ram (10) may apply a compressive force along the length of the magnetostrictive material to bias a drill bit (2) against the rock (1).

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Magnetostrictive Actuator

This invention relates to a magnetostrictive actuator, and in particular to a magnetostrictive actuator for use in a percussive rock drill.

In a percussive rock drill, a drill bit is repeatedly forced against a rock surface, whilst being rotated about its own axis. This produces high local stresses in the rock surface which cause the rock to fracture. The fractured rock is flushed away from the bit surface and back along the drilled hole by a flushing fluid introduced for that purpose.

It is conventional to use hydraulic energy to move a hammer backwards and forwards against the drill bit to produce the percussive action. However the use of hydraulic energy in this way produces efficiency levels which are lower than could be desired, and the necessity to route hydraulic hoses to and from the hammer unit can cause problems.

It is an object of the present invention to provide an actuator and a rock drill that address some of these problems.

According to the present invention, there is provided a magnetostrictive actuator for applying a pulsating pressure, comprising an applicator with a magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field, characterised in that the drive means has a plurality of coils supplied in parallel with an electric drive current pulsed at a drive frequency from one or more drive

circuits.

Each expansion in length of the magnetostrictive material, which may be shaped as a rod with a circular, square or hexagonal cross-section, produces a corresponding movement of the magnetostrictive unit.

The applicator preferably has biasing means to apply a compressive force along the length of the magnetostrictive material. Such pre-loading or pre-stressing of the magnetostrictive material will, up to a certain pressure, improve the efficiency with which magnetic energy is converted into pulsating energy.

The multiple coils may be driven by a single drive circuit, but it is advantageous in order to lower the amount of current or power that has to be delivered by a drive circuit if each coil has its own drive circuit, which may then be individually controllable by the drive means.

The drive circuit will typically be supplied by a fixed voltage ac power source, although the drive circuit could be designed to run from a variable voltage source, with the drive circuits supplying current to the coils, for example through FETs. The coils may also be driven in electrical resonance.

Multiple coils can each have a lower individual inductance than a corresponding single coil, which permits lower coil driving voltages and/or faster current rise times and consequent higher achievable pulsating frequency.

In one arrangement, the coils comprise coaxial sheets of conductor wrapped, at least once, about the magnetostrictive material. Conductive leads may then

supply the drive current to the coils.

In another arrangement, each coil comprises loops of conductor wrapped about the magnetostrictive material at points spaced from other coils along the length of the material.

The coils may be at least partially inductively decoupled by intervening flux closure elements. Each coil may conveniently be the same as every other coil, having the same dimensions and number of turns, in order to simplify manufacture or repair of the magnetostrictive unit.

The magnetostrictive material is preferably held within a sleeve which is close fitting around the sides of the material and open at the ends. The ends of the material may also bear against end pieces, one of the end pieces being fixed and another of the end pieces being movable upon a change in the length of the magnetostrictive material. The sleeve may align and at least partially enclose the end pieces.

End plates may be provided to hold the coils in place within the magnetostrictive unit. The end pieces, end plates, and particularly the sleeve have to hold the magnetostrictive material securely in order to prevent bending and consequent fracturing of the material under the high compressive stresses present during actuation.

The coils may be integrally bonded one with another, but it is generally preferred if the coils are held securely and separable from each other. For example, the coils may be separated by spacer elements which extend from the sleeve. Then if a coil fails for any reason, the magnetostrictive unit may be disassembled to replace or repair the defective coil, without having to discard the

complete coil assembly.

The spacers may conveniently be integral with the flux closure elements. For example, the spacers could be steel shims or discs and may optionally provide additional electrical insulation between the coils. Alternatively, the spacers could comprise a non-magnetic metal, which may have a higher thermal conductivity than steel, such as copper. The shielding effect of one coil from another may then be provided at the drive frequency by the skin effect in the surfaces of the copper adjacent to neighbouring coils.

During operation of the actuator, heat will be generated in the magnetostrictive unit from such sources as electrical resistance in the coils and eddy currents generated by self-inductance between coils and in conductive components including the magnetostrictive material itself. Above a certain operating temperature, the coils may become damaged, and the efficiency of the magnetostrictive actuator may drop off. In order to achieve a sufficiently high actuation rate, it will for many applications be necessary to have a cooling circuit that circulates a gas or liquid cooling fluid, such as air, oil or water, through the applicator to remove excess heat from the magnetostrictive unit.

To improve the efficiency of the cooling, the cooling circuit may be incorporated with the spacers or the flux closure elements to cool between the coils, and to remove excess heat from the magnetostrictive material inside the coils. The coolant may flow inside channels in the spacers, or alternatively if the spacers have a high enough thermal conductivity, the spacers may simply conduct heat out of the coil assembly towards the cooling circuit.

The sleeve may also contain cooling channels as part of the cooling circuit.

If the current pulses all have the same polarity, then the magnetostrictive unit will be pulsed once for each cycle of the drive frequency. In this case, each pulse may last for about a half-cycle.

However, current may be pulsed in both positive and negative directions so that the frequency of the magnetostrictive unit may be doubled relative to the drive frequency. In this case each of the two mechanical pulses per cycle may last about one-quarter cycle. The actuation rate may therefore be effectively doubled, without the need for using a higher drive frequency with the consequent need for higher drive voltages and/or lower coil impedances.

Ideally, the magnetic field applied to the magnetostrictive material should not drop off towards the ends of the coil arrangement. Although the magnetic field may be substantially constant through the middle of the magnetostrictive material, field lines may diverge at the coil ends so reducing field strength. In order to ameliorate this effect and produce a more even magnetic field profile along the length of the magnetostrictive material and so optimise the performance of the magnetostrictive unit throughout its length, the drive means may optimally be arranged to supply more current to the coils nearer the coil ends than to coils farther from the coil ends. The amount of the current may be increased either by increasing a drive voltage supplied by the drive means, or by increasing the on/off duty cycle of the current. Alternatively, the current may not be varied, and the dimensions of the coils or the number of turns may be varied towards the ends of the coil arrangement.

The ability to control the amount of current provided to each coil may also be used to compensate for changes in relative permeability along the length of the magnetostrictive material due to such factors as variation in composition, or crystal grain misalignment.

When the coils are separately driven, the drive means may actuate coils with drive current at different times. By independently controlling the on and off time of each pulse different coils may be driven at different duty cycles.

The on and off times may be varied in a synchronised manner from one end of the magnetostrictive unit to the other, so that the on times from one coil to the next are delayed by an interval comparable with speed of sound in the magnetostrictive material. It may then be possible to produce a travelling mechanical wave pulse along the length of the magnetostrictive material, as each coil is successively actuated in turn. This results in a superimposing effect with the pulsating mechanical pulses arising from each coil arriving at the end of the magnetostrictive unit or applicator essentially superimposed and so increasing the pulsating pressure that may be applied.

The magnetostrictive unit may also be driven in mechanical resonance, so that the drive frequency matches the natural frequency of longitudinal compressive waves for the actuator. Resonant operation improves the efficiency of the actuator by increasing the amplitude of the pulsating action and/or decreasing the required electrical drive power. The resonant frequency of the magnetostrictive unit will, in general, be affected by the presence of other items in contact with the magnetostrictive unit, such as the biasing means. The biasing means may be a

hydraulic ram in line with the magnetostrictive material.

In another arrangement, the drive circuitry has means to modulate the drive current during a current pulse in order to modulate similarly the pressure applied by the magnetostrictive unit.

It is preferred if the applicator comprises a gauge or load cell, which is preferably in the magnetostrictive unit in contact with one end of the magnetostrictive material to measure the pressure applied by the magnetostrictive unit or applicator, and also feedback means for controlling this pressure. The gauge or load cell may provide a signal representative of the pressure to the feedback means which then may use this signal to control the applicator and may in particular control the magnetostrictive unit.

Because the instantaneous pressure will vary rapidly during one cycle of the magnetostrictive unit, the signal from the gauge may most usefully be an average over several cycles.

The feedback means may be arranged to increase the pressure or compressive force exerted by the biasing means if the measured pressure falls below a predetermined point. This feedback is advantageous because it helps to protect a magnetostrictive rod from mechanical failure. The feedback means may then be arranged to control both the pre-stress in the magnetostrictive material and the thrust applied to a drill bit.

The feedback means may, of course, provide the inverse feedback upon an increase in the average pressure measured by the gauge.

In a further embodiment of the invention, instead of a fixed voltage and frequency ac power source, the applicator comprises an electric generator for synchronously driving the drive means at the drive frequency. The generator may be driven by a hydraulic supply line, so avoiding the need to run electric cables long distances to the actuator.

The generator may conveniently be driven at a frequency in direct proportion to the frequency of the actuator. This is because the output voltage from an electric generator varies proportionately with the generator frequency in the same ratio as the optimum drive voltage for a coil needed to keep the current rise time within the coil to a constant fraction of the period of the coil drive frequency. The drive means may therefore automatically be arranged to increase the coil drive voltage.

The magnetic field may be pulsed at a frequency varying between or set between 0 and 1 kHz, although in some applications a pulsating frequency of up to about 2 kHz may be desirable.

The magnetostrictive material is preferably that known under the trade mark Terfenol. This is a metallic compound containing the rare earth elements dysprosium and terbium, together with iron. Terfenol has very good magnetostrictive properties, that is, it produces a relatively high change in length on application of a magnetic field. This change in length can be about 0.1 percent.

Also according to the invention, there is provided a magnetostrictive rock drill, comprising a drill bit adapted to bear against the rock; and a magnetostrictive

actuator for applying a pulsating pressure, comprising an applicator with a magnetostrictive unit having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field, characterised in that the drive means has a plurality of coils supplied in parallel with an electric drive current pulsed at a drive frequency from one or more drive circuits, the magnetostrictive actuator being arranged so that it may force the bit with sufficient pressure to fracture the rock.

The action of the movement of the magnetostrictive unit causes the drill bit to be forced against the rock. In a typical installation, the drill bit will be at one end of a drill string and the magnetostrictive material will be arranged so that it applies a force to the other end of the drill string. Thus the magnetostrictive material may be "down the hole" and directly behind the drill bit or it may alternatively be spaced from the drill bit by a considerable length of compression pulse transmitting drill rods.

In general, the presence of the drill bit, rods, etc., will affect the resonant frequency of the magnetostrictive unit.

The voltage required of the power source or from the drive circuits may be minimised if the inductance of the coils are suitably reduced by minimising the number of turns on the coils. Another way of minimising the voltage is to add capacitance to the drive circuits so that the coils may be driven in electrical resonance at the drive frequency.

In order to ensure that all of the axial expansion of the magnetostrictive material is transmitted to the drill bit, the magnetostrictive material is pre-loaded by a ram to force the body of the material against the bit and bias the drill bit against the rock, prior to magnetostrictive action. The action of the ram will apply a compressive force to the length of the magnetostrictive material and so is equivalent to the biasing means described above, and the feedback means may control the ram pressure.

A gearbox is preferably provided between the magnetostrictive unit and the drill bit, to rotate the drill bit as the pulsating force is being applied.

The use of multiple coils permits the impedance of each coil to be reduced in comparison with the impedance of a single equivalent coil. A lower impedance is desirable because it permits during a current pulse a relatively faster rise time for a given voltage provided by the drive circuitry. A faster rise time permits a greater drive frequency and hence a higher and more efficient drilling rate. Higher voltages, and particularly voltages above 1 kV are undesirable owing to the greater difficulty of safely insulating electrical components or running electrical cables in a mining environment which may, in some cases, be very humid and hot.

The invention will now be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic block diagram showing a magnetostrictive rock drill according to the invention, having a magnetostrictive unit with associated electronics;

Figure 2 is a graph showing the relationship between strain and applied magnetic field for a magnetostrictive material;

Figure 3 is a cross-section through the magnetostrictive unit of Figure 1 showing a multiple coil and spacer arrangement;

Figure 4 is a plan view of one of the spacers of Figure 3;

Figure 5 is a cross-section though the spacer of Figure 4, taken on the line V-V.

Figure 6 is an end view of an anti-rotation element;

Figure 7 is a cross-section through the anti-rotation element of Figure 6, taken on the line VII-VII; and

Figure 8 is an enlarged cross-section through the magnetostrictive unit of Figure 1 illustrating magnetic circuits and a cooling arrangement.

Figure 1 shows a rock face 1 to be drilled, with a drill bit 2 about to be placed in initial contact with this rock face. The bit 2 is mounted at the end of a drill rod 3, the other end of which terminates in a pulsating force magnetostrictive unit generally indicated at 4.

As drilling proceeds, the bit 2 will form a hole in the rock face 1. Depending on the length of the hole to be drilled, it may be necessary to interrupt the rod 3 to extend it by inserting further lengths of drill rod in a known manner.

Also in a known manner, the fractured rock is flushed away from the bit surface and back along the drilled hole by a flushing fluid 12 such as air or water introduced for that purpose into the base of the drill rod 3 and ejected 13 through the drill bit 2.

The drill rod 3 is supported by and passes through a pair of mounts 5,6 between which is a rotary drive 7 and gearbox 8 for rotating the drill rod and bit.

The magnetostrictive unit 4, mounts 5,6 and rotary unit 7,8 are all mounted and held in a fixed relationship to each other on a beam 9. A hydraulic ram 10 applies a bias pressure to the back of the magnetostrictive unit 4, and moves the beam forward as the drill bit cuts into the rock.

Control and drive electronics are shown schematically for a closed loop system and generally indicated at 11. The electronics 11 may conveniently be integrated in a separate unit mounted on the beam 9 in proximity with the magnetostrictive unit 4.

Magnetostriction is the fractional change in length of a material obtainable by the application of a magnetic field. It is usually anisotropic and volume conserving. The magnetostrictive material in the magnetostrictive unit is known under the trade mark Terfenol-D ($Tb_xDy_{1-x}Fe_y$ where $0.27 \le x \le 0.32$ and $1.92 \le y \le 2.0$). Terfenol-D can withstand a high uniaxial stress of up to 350 MPa. The tensile strength however, is only, at most, 25 MPa.

Figure 2 shows the general Strain λ vs. Magnetic Field H relationship for Terfenol-D at different levels of pre-stress. The magnitude and efficiency of the achievable strain for a given magnetic field is a maximum if a pre-

stress of about 7 to 15 MPa is first applied. This is due to magnetoelastic effects. Strains λ greater than 0.1% can readily be achieved in Terfenol-D with moderate magnetic fields of about 120 kA/m.

The efficiency of the conversion of magnetic energy into strain is greatest where the slope of the curve is maximum at point H_b. For some applications it may be desirable to bias the Terfenol-D in the approximately linear region at the point B on the curve, either with static magnets or with a constant bias current in a coil arrangement.

When using Terfenol-D for rock drilling, it is desirable to pre-stress the material to approximately 15 to 30 MPa. The optimum level of pre-stress will depend upon the grain structure and other characteristics of the magnetostrictive material.

A simple calculation illustrates the feasibility of using a Terfenol based actuator to drill rock. A 500 mm long rod of Terfenol-D may expand upon application of the field by 0.5 mm. A conventional drill bit may have a contact area A_c with rock of 6.6×10^{-5} m^2 upon penetrating the rock by 0.5 mm. The required force needed to achieve 140 MPa pressure would then be 9257 N. Under steady state conditions, the force applied by the Terfenol-D will be $F = E \times A_r \times \lambda$, where E is Young's Modulus which is estimated to be about 30 GPa, A_r is the cross-sectional area of the rod which is here 20 mm in diameter, and λ is 0.1%. The available magnetostrictive force is then 9425 N, which is more than sufficient to fracture such rock, even before taking into consideration the additional force available from the pre-stress.

Figure 3 shows in more detail the internal construction of the generally cylindrical magnetostrictive unit 4, and

the interface of this unit to the drill rod 3 and hydraulic ram 10. A Terfenol-D rod 30 is housed along the central axis of the magnetostrictive unit inside a close fitting non-magnetic support sleeve 31. One end of the rod abuts a fixed end piece 32 made from hardened steel, and the other end is free to expand and contract a limited distance in contact with another end piece in the form of a cylindrical hardened steel load cell 33 which in turn contacts an anti-rotation element 34. The movement of the Terfenol-D rod 30 is transmitted through the load cell and anti-rotational element 34 to the drill rod 3.

The anti-rotational element 34 is shown in more detail in Figures 6 and 7. This element decouples the rotary motion of the drill bit from the magnetostrictive activator material. The anti-rotational element 34 consists of a cylindrical body with one end 70 having a flat face and the other end having a flat face 71 with a cylindrical recess 72 for receiving one end of the load cell 33. A rib 73 with a roughly square cross-section extends radially outwards from the side of the element, and in use is seated within a matching recess

The sleeve 31 extends beyond the ends of the Terfenol-D rod 30 in order to hold and align the end piece 32 and the load cell 33.

The sleeve is formed from a resilient glass fibre reinforced plastics material such that sold under the trade mark Tufnol, grade 10G/40. The Terfenol-D rod 30 can shatter if it is forced out of alignment during assembly or during pulsed operation of the magnetostrictive unit. In order to constrain the rod from bending during operation the tolerance between the sleeve and rod should be as close as possible, and ideally the sleeve should be stiff, too. However, these two

requirements are incompatible with the relative fragility of the Terfenol-D rod which, for example, may shatter owing to inadvertent bending during insertion into a close fitting metal or ceramic sleeve. The sleeve may also have to support at least some of the weight of the coil assembly which surrounds it, at least during assembly of the magnetostrictive unit. A tough plastic sleeve has therefore been found to have a good combination of properties for this application.

As a more durable alternative to Tufnol plastic, a ceramic material may be used for the sleeve.

A total of forty-two independent wire-wound coils 35 surround the sleeve, extending in length somewhat more than the length of the Terfenol-D rod. Each of the coils 35 is separated from its neighbour by dividing plates 36, one of which is shown in more detail in Figures 4 and 5. The dividing plate has a central circular hole 42 for the sleeve 31. A narrow rectangular aperture 43 runs between the hole 42 and the outer periphery of the divider for allowing one end of the wire forming a coil to be returned to the outside of the coil assembly. Around the periphery are a further twelve evenly spaced holes 44 for tie rods 37.

The coil dimensions are an inside diameter of 50 mm, an outer diameter of 200 mm, a thickness of 10 mm. With a wire diameter of 0.8 mm, each coil has a resistance of 23 Ω and an inductance L of 210 mH. Each coil is pulsed in phase with a square wave train consisting of a series of positive and negative voltage pulses, each pulse being between 15% to 25%, and most typically 25%, of the full duty cycle. The Terfenol-D expands upon each pulse, and so rectifies the electronic signal to a pulsating action at double the electronic frequency. For a unidirectional

drive current, each voltage pulse would most typically be 50% of the full duty cycle. At a 1 kHz sine wave electrical frequency ν the reactance $2\pi\nu I$ of each coil would be 1319 Ω. Operation can be achieved at a supply current of about 3 A, and since the power requirement equates to the energy stored in each coil $\frac{1}{2}LI^2 = \frac{1}{2}\cdot(210\ mH)\cdot(9\ A^2) = 0.945\ J$ plus heating losses (I^2R), the total power requirement is about 42 kW.

Before assembly of the magnetostrictive unit 4, each coil 36 is wound and baked on a form to make a solid cylindrical pancake. The forty-two coils are then assembled over the sleeve with the spacers, with an end plate 38 machined from Tufnol plastic, at each end. Behind the Tufnol end plates are steel end plates 39,40, which tie the coil assembly together with the twelve tie rods 37.

The coil assembly is then encased in an outer protective steel shell 41. In order to reduce the mass of the steel, this shell 41 may be encased in an outer protective plastic envelope (not shown).

If an electrical fault in a coil develops later on, the magnetostrictive unit 4 may be readily disassembled and the defective coil replaced.

The use of a plurality of coils, each independently supplied with current, allows the operating voltage for each coil to be lower than for an equivalent single coil. A magnetostrictive rock drill may have a pulsating frequency of about 1 kHz for a high drilling rate. For a single coil magnetostrictive actuator, this would imply an operating voltage of several kilovolts owing to the high coil impedance.

Mutual inductance between coils of a multiple coil arrangement would make the inductance comparable with a single coil arrangement. As illustrated schematically by arrows in Figure 8, to minimise this self-coupling effect, the spacers 36 need to made from a magnetic material, such as steel coated with an insulating material, in order to direct flux closure loops from each coil so that these loops enclose mainly the one coil, with a progressively smaller proportion of flux closure loops enclosing adjacent and further coils.

Alternatively, the spacers could be made from a non-magnetic but conducting material, such as copper, as long as the thickness of the spacers was sufficient so that at the magnetostrictive unit operating frequency, the skin depths of eddy currents in the spacers are sufficient to shield one coil from its neighbours.

As indicated by the arrows in Figure 8, the tie rods 37 and the outer casing 41, both being made from steel, will also contribute to closing the magnetic circuits for each coil.

Since a full size magnetostrictive rock drill may consume about 42 kW of electrical power, and about two-thirds of this may be usefully converted into drilling energy. The remaining approximately 13 kW of energy will be left as heat within the magnetostrictive unit, and will have to be removed by an active cooling circuit, since the performance of Terfenol-D deteriorates rapidly at temperatures above 150°C. Figure 8 shows the two ends of the magnetostrictive unit 4 with four cooling water inlets 81-84, and four corresponding outlets 85-88, two of which are in the steel outer case 41, and two of which are bored in the non-magnetic Tufnol plastic sleeve 31. Other cooling channels will be spaced circumferentially around

the magnetostrictive unit. The metal spacers 36 help conduct heat out of the coils towards the cooling circuits.

Returning now to the description of the drive and control electronics 11, each coil is provided with its own drive circuit, all of which operate at the same frequency. Each drive circuit generates square positive and negative voltage pulses which can be individually controlled, both in terms of the voltage applied and the width of the pulse. The magnetic field amplitude at the coil ends will naturally be less than in the centre of the coil arrangement because of fringing effects. The drivers at these end positions are therefore adjusted to boost the voltage to compensate the field amplitude.

The signal from the load cell 34 is averaged and fed to a closed loop feedback circuit which controls the ram 10 feed pressure. The feedback to the ram 10 helps to maintain feed pressure by varying the ram pressure inversely with pressure as measured by the load cell, in order to keep the total pressure supplied by the magnetostrictive drill within certain bounds.

It may, of course, alternatively be possible to implement at least some of this control in an open loop system with an operator manually adjusting the ram and/or the magnetostrictive unit.

Finally, the rotation rate of the rotary unit 7,8 may optionally be synchronised with the frequency of the coil drive, so that as the coil drive frequency increases, so does the speed of the rotary unit.

Because the magnetostrictive unit 4 is held rigidly in position, the axial expansion of the Terfenol-D rod 30

causes the drill rod 3 and the drill bit 2 to be forced against the rock 1 to cause high local stresses in the rock, leading to fracturing.

When the magnetic field in the coils 35 is pulsed, ie repeatedly turned on and off, then the repeated expansion and contraction of the rod 3 will produce a pulsating action of the bit 2 against the rock, and this will produce a drilling action, especially when combined with rotation of the bit 2 through the rotary drive 7,8.

It is a property of magnetostrictive materials, that when the magnetic field is removed, the material returns to its original shape without requiring any externally imposed restoring force. The return to original shape may be accompanied by some hysteresis. In the preferred embodiment of the invention, there is in fact an externally imposed restoring force resulting from the pressure exerted by the hydraulic ram 10 continually pressing the bit against the rock surface.

The magnetostrictive material will be prepared so that it has a preferential axial extension, when placed in a magnetic field. The dimensions of the magnetostrictive rod 30 will be determined, <u>inter alia</u>, in accordance with the hardness of the rock being drilled and the diameter of the hole to be drilled. It is expected however that in general the length of the rod will be from 500 mm to 1000 mm and that the diameter of the rod will be from 20 mm to 25 mm. Larger dimensions will be used for harder rock. The length of the rod may be increased by abutting and gluing rods end to end, and larger diameter rods may be formed by cutting rods into a hexagonal cross section, and then gluing rods side by side.

Rods may also be cut lengthwise into several strips, and

then laminated together with insulating glue, in order to reduce shielding skin effects due to eddy currents, and so improve high frequency performance. For example, at 2 kHz, the skin depth δ of Terfenol-D having a relative permeability μ_r of 2 to 5 and a conductivity κ of $1.6 \times 10^6\ \Omega^{-1}m^{-1}$ is 6.4 mm to 4.2 mm. Accordingly, at 80 kHz, the skin depth would be typically in the range 1.0 mm to 0.67 mm. Since the drive current may contain frequency components above a 2 kHz drive frequency, a 20 mm diameter Terfenol-D rod may be laminated from 2 mm thick slices.

For some types of rock drilling, however, a high frequency may not be necessary. For example, satisfactory results have been obtained in softer types of rock at frequencies as low as 30 Hz, which is comparable to the frequencies used in conventional hydraulic hammer drills. Higher frequencies, of the order of 1 kHz or 2 kHz, may be usefully employed in hard rock drilling.

The efficiency of magnetostrictive materials in converting externally provided energy to an axial force is high compared with the corresponding efficiency of hydraulic mechanisms. Furthermore the pulsating force applicator only requires connection in an electrical circuit, and electrical cables can in some circumstances be handled more easily than hydraulic hoses. The drill described therefore makes use of the magnetostrictive effect to produce an effective and efficient apparatus for percussive or pulsating rock drilling.

Claims

1. A magnetostrictive actuator for applying a pulsating pressure, comprising an applicator (4,10,11) with a magnetostrictive unit (4) having a length of magnetostrictive material and drive means for subjecting the material to a pulsed magnetic field to produce a change in the length of the material on each pulse of the magnetic field, characterised in that the drive means has a plurality of coils supplied in parallel with an electric drive current pulsed at a drive frequency from one or more drive circuits.

2. A magnetostrictive actuator according to Claim 1, in which the applicator (4,10,11) has a biasing means (10) to apply a compressive force along the length of the magnetostrictive material.

3. A magnetostrictive actuator according to Claim 1 or Claim 2, in which each coil has its own drive circuit individually controllable by the drive means.

4. A magnetostrictive actuator according to any preceding claim, in which the coils are at least partially inductively decoupled by intervening flux closure elements.

5. A magnetostrictive actuator according to any preceding claim, in which the ends of the magnetostrictive material bear against end pieces, one of the end pieces being fixed and another of the end pieces being movable upon a change in the length of the magnetostrictive material.

6. A magnetostrictive actuator according to any preceding claim, in which the applicator (4,10,11) has a

cooling circuit to remove excess heat from the applicator.

7. A magnetostrictive actuator according to any preceding claim, in which the magnetostrictive material is held within a sleeve which is close fitting around the sides of the material and open at the ends.

8. A magnetostrictive actuator according to Claim 7 when appendant to Claim 6, in which the sleeve contains cooling channels as part of the cooling circuit.

9. A magnetostrictive actuator according to Claim 7 or Claim 8, in which coils are separated by spacer elements which extend from the sleeve.

10. A magnetostrictive actuator according to Claim 9 when this is appendant to Claim 6, in which the spacers are integral with the flux closure elements.

11. A magnetostrictive actuator according to Claim 9 or Claim 10, in which the spacers comprise cooling channels through which a cooling fluid may be passed to cool between the coils.

12. A magnetostrictive actuator according to any preceding claim, in which the drive circuits pulse drive current at the drive frequency through the coils in both positive and negative directions in order to double the frequency of the magnetostrictive unit (4) relative to the drive frequency.

13. A magnetostrictive actuator according to any preceding claim, in which the drive means actuate coils with drive current at different times to produce a travelling wave pulse along the length of the magnetostrictive material.

14. A magnetostrictive actuator according to any preceding claim, in which the magnetostrictive unit (4) is driven in mechanical resonance.

15. A magnetostrictive actuator according to any preceding claim, in which the coils are driven in electrical resonance.

16. A magnetostrictive actuator according to any preceding claim, in which the drive circuitry has means to modulate the drive current during a current pulse in order to modulate similarly the pressure applied by the applicator (4,10,11).

17. A magnetostrictive actuator according to any preceding claim, in which the applicator (4,10,11) comprises a gauge to measure the pressure applied by applicator and feedback means for controlling the pressure applied by the applicator, in which the gauge provides a signal representative of the pressure to the feedback means which then uses this signal to control the applicator.

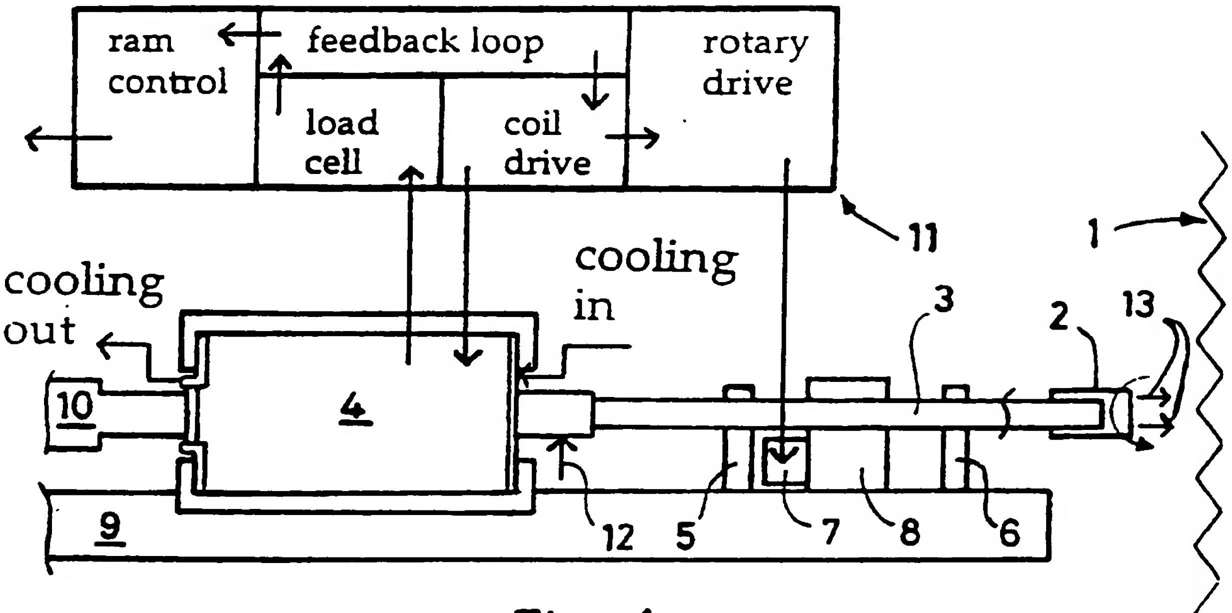
18. A magnetostrictive actuator according to Claim 17, in which the feedback means increases the biasing means pressure if the measured pressure falls below a predetermined point.

19. A magnetostrictive actuator according to any preceding claim, comprising an electric generator for synchronously driving the drive means at the drive frequency.

20. A magnetostrictive actuator according to any preceding claim, in which the magnetic field is pulsed at a frequency of at least 30 Hz.

21. A magnetostrictive rock drill, comprising a drill bit (2) adapted to bear against the rock (1), and a magnetostrictive actuator (4,10,11) according to any one of Claims 1 to 20 arranged so that it may force the bit (2) with sufficient pressure to fracture the rock (1).

22. A magnetostrictive rock drill according to Claim 21, in which the applicator (4,10,11) has a ram (10) to bias the drill bit (2) against the rock (1).


ram control
feedback loop
load cell
coil drive
rotary drive
cooling out
cooling in
4
10
9
11
1
3
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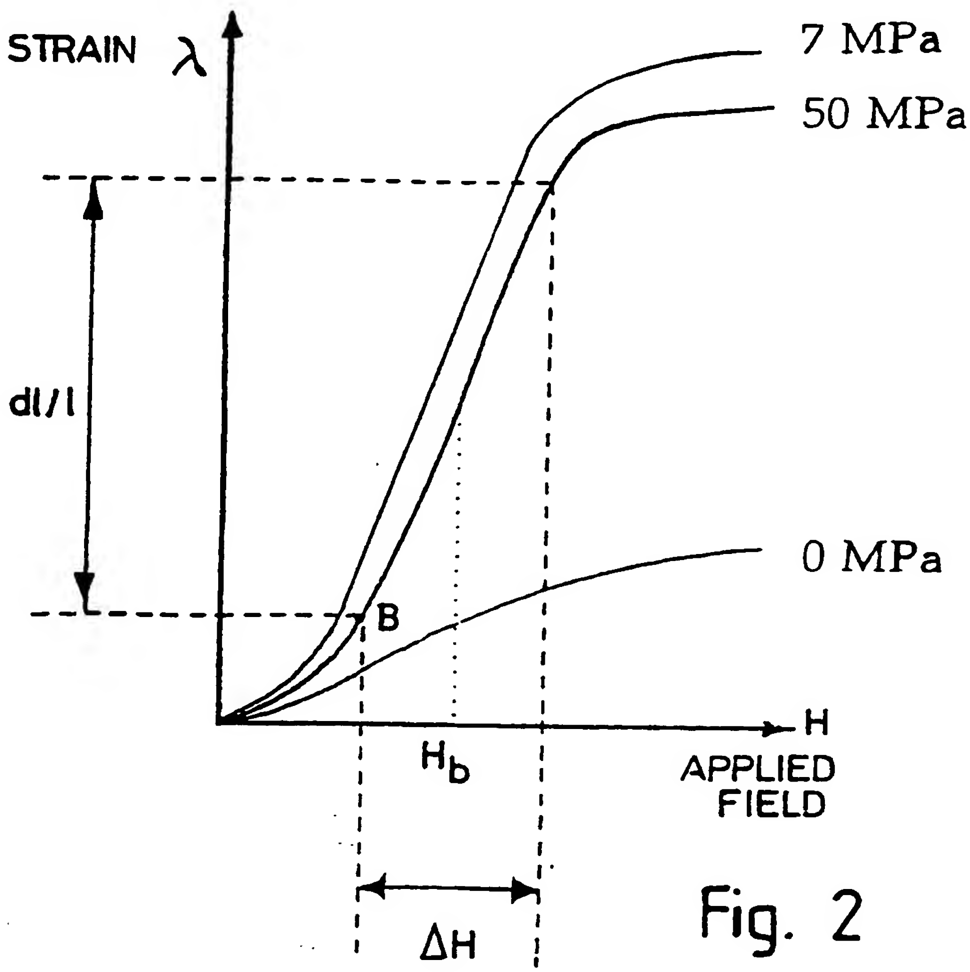
5
7
8
6

Fig. 1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50 MPa
0 MPa
dl/l
B
H
H_b
APPLIED FIELD
ΔH

Fig. 2

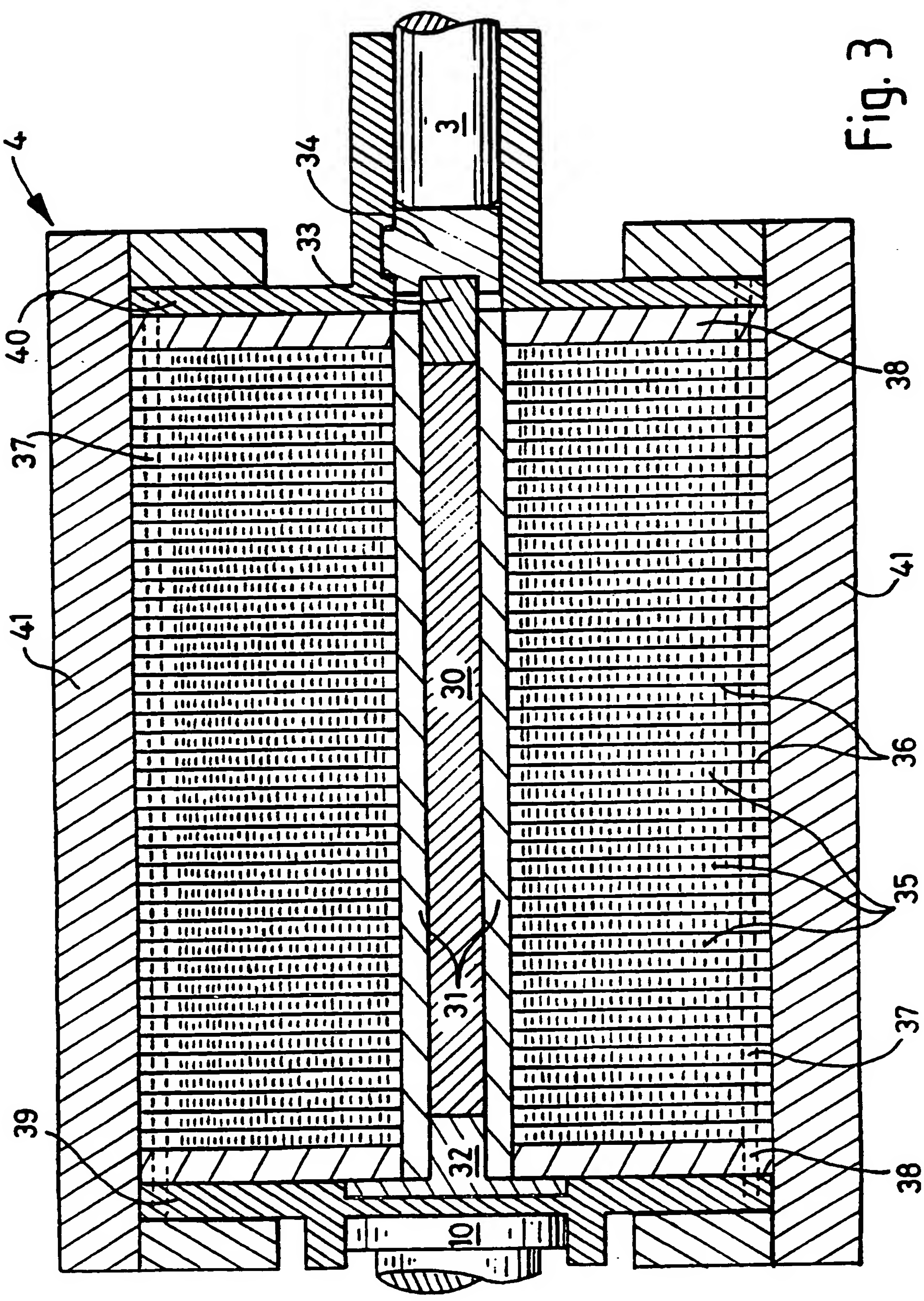

Fig. 3

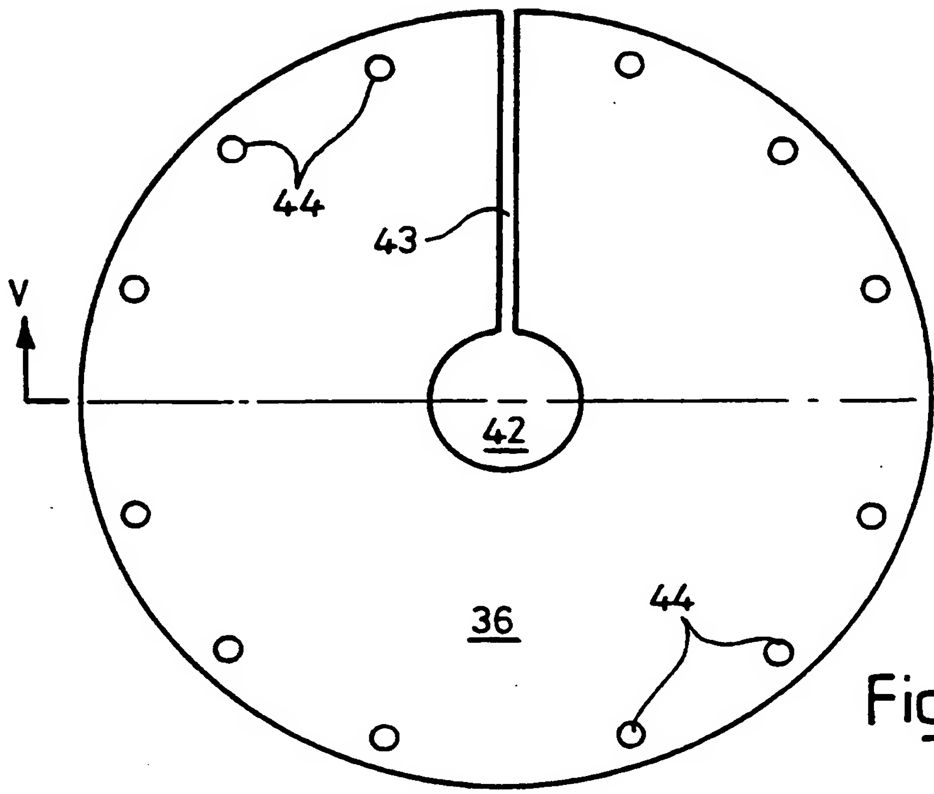

Fig. 4

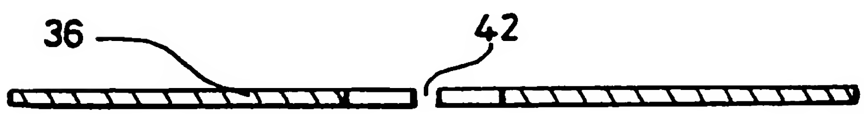

Fig. 5

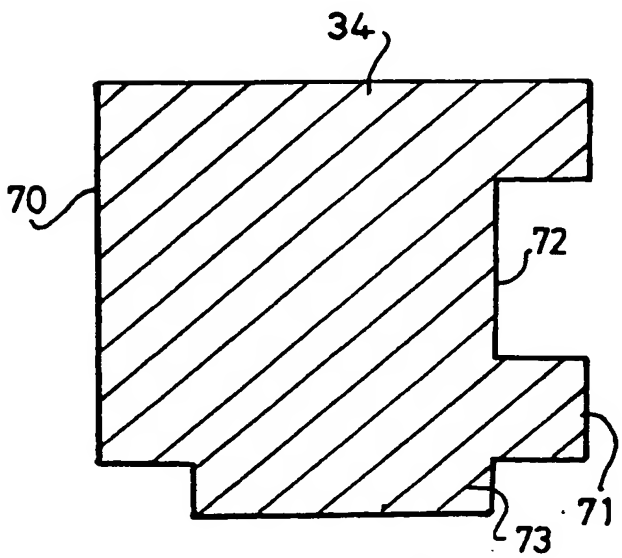

Fig. 7

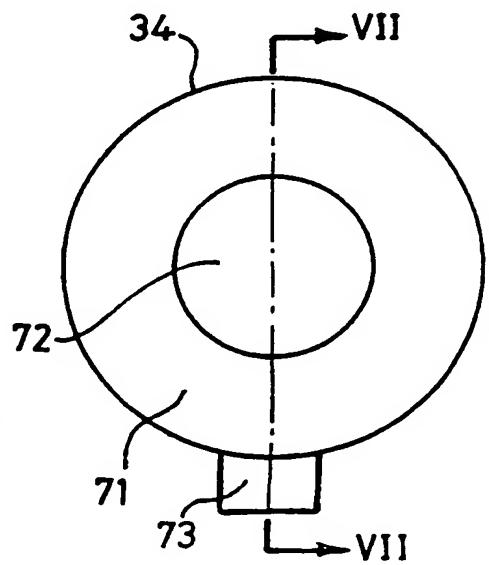

Fig. 6

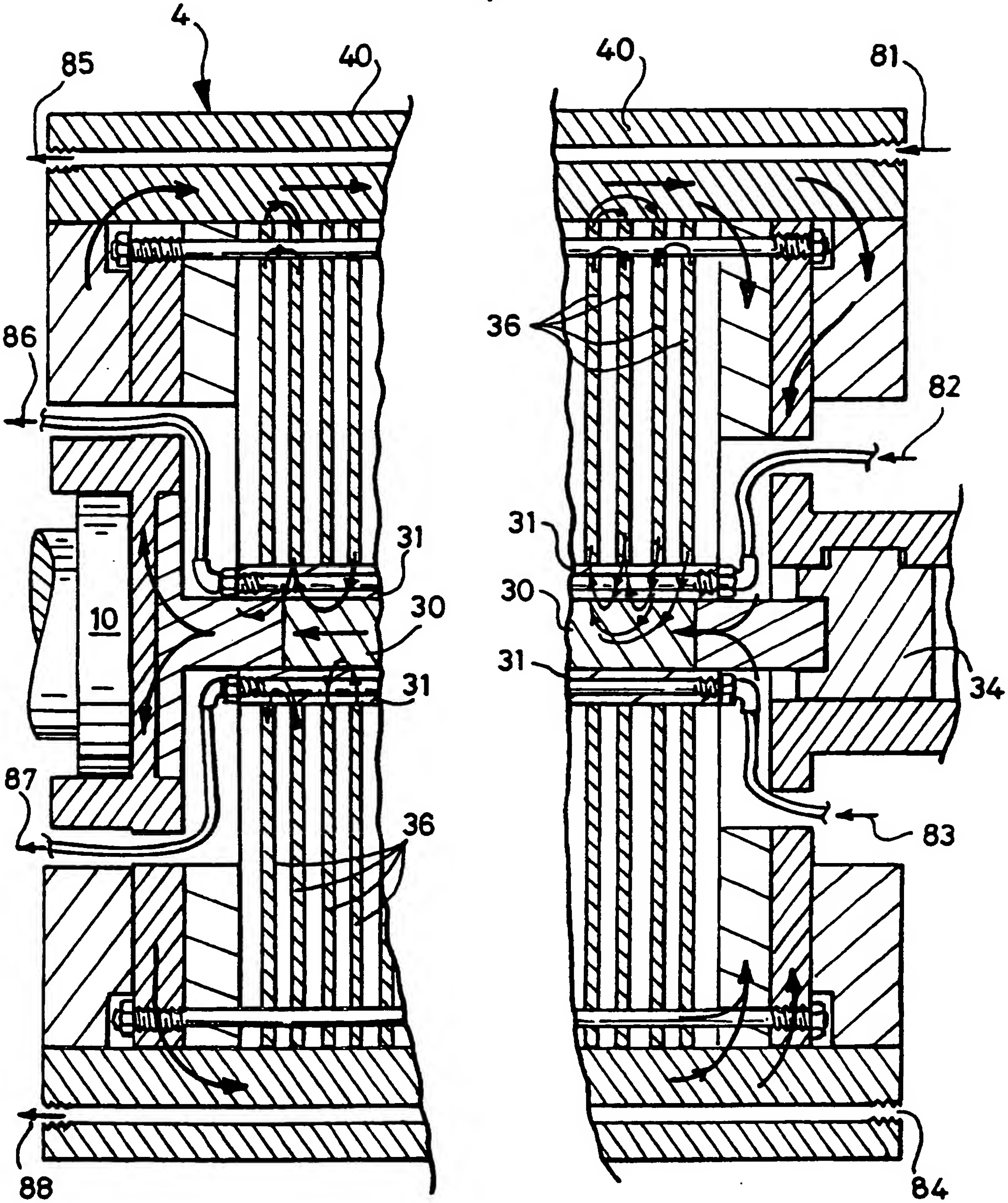

Fig. 8